Marine Boundary Layer Processes In The Littoral Zone

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LONG TERM GOALS

The long-range goal of this project is to understand and interpret atmospheric structures in the littoral zone to improve the prediction of boundary layer processes on scales of 1 km to 100 km. This region of the atmosphere is complex, influenced by the competing effects of topography and differential heating. Large spatial and temporal variations in many fields are expected, but poorly predicted. The processes that control the distribution of aerosols, the formation, evolution and dissipation of clouds and fog, the variability of the wind field and thermodynamic structure of the atmosphere in the littoral zone need to be understood.

SCIENTIFIC OBJECTIVES

The specific scientific objectives of this project are to determine the along-shore and cross-shore ageostrophy of the mean atmospheric flow forced by the adjacent coastal mountain barrier; to characterize the interaction of the orographically-forced flow with the mean thermal circulation associated with the daytime sea breeze and sea surface temperature gradients; to characterize the offshore variability of the boundary layer, its turbulent structure and the influence of the barrier and thermal gradients on the development of coastal clouds and fog; and to determine the distribution, sources and sinks of aerosols in the marine boundary layer.

APPROACH

The small space and time scales associated with the coastal zone place severe demands on measurement systems to resolve the complex interactions between orographically constrained flow, across-shore thermal gradients and the upper ocean. Aircraft in situ and remote sensing techniques provide the necessary spatial and temporal resolution of the atmospheric boundary and sea surface fields.

Three related field campaigns have been completed as part of this study: Monterey Area Shiptracks (MAST) experiment, SHAREM 115 in the Persian Gulf, and the Coastal Waves 96 (CW96) experiment along the coast of California. The first two studies were focused on observations obtained with the UK Met. Research Flight C-130 aircraft. The latter focused on observations obtained with the NCAR C-130 during the Coastal Waves experiment.

The main focus of of this report is the analysis of data collected during SHAREM 115 and CW96. SHAREM 115 is a collaborative study with Dr. Andreas Goroch at NRL, Monterey. Dr. Goroch is the primary liaison with the US Navy for this project and responsible for ship based observations. CW96

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is a collaborative study with Drs. Clive Dorman at SIO, Steve Burk and William Thompson at NRL, Monterey, and Michael Tjernström at University of Uppsälä. Dr. Dorman is primarily responsible for the surface measurments and shares responsibility for the aircraft field program, which was partly supported by the NSF. Drs. Burk and Thompson are responsible for various modeling tasks associated with the CW96 program using COAMPS. Dr. Tjernström is responsible for various modeling tasks using the University of Uppsälä atmospheric model.

WORK COMPLETED

Two reports on the results of SHAREM 115 have been completed for the Office of Naval Research (ONR) and the United Kingdom Ministry of Defence (UK MOD). The purpose of these reports was to satisfy UK MOD scientific requirements for future participation in bilateral naval exercises designed to test new electro-magnetic / electro-optical (EM/EO) systems for near surface targets. These reports were promulgated at the Meteorological Research Flight Military Users Meeting held at ONR Europe. Two peer reviewed papers have been published.

Numerous conference proceedings and peer reviewed journal articles have been published from the CW96 program. We have completed all of our proposed objectives.

RESULTS

The focus of this year's effort has been to continue the analysis of data collected during the SHAREM 115 and CW96.

SHAREM 115

SHAREM-115 was a Naval exercise conducted during 1996 in the Persian Gulf. The UK Meteorological Research Flight C-130 Hercules participated to obtain battlespace atmospheric conditions. A study of radar propagation conditions demonstrates that the variability in duct depth and strength is significant. This variability is shown to result in serious errors in model estimates of propagation range if the common assumption of spatial homogeneity of ducting conditions is made. Variability of the trapping layer associated with the boundary layer inversion results from the combined influences of boundary layer modification following advection from over land to a marine environment and mesoscale subsidence. These changes are gradual and amenable to prediction by mesoscale models. However, on one occasion a very sharp and substantial change in ducting conditions was observed. It is postulated that this transition results from mixing across the inversion, probably due to the breakdown of Kelvin-Helmholtz waves. A paper has recently appeared in the Journal of Applied Meteorology reporting these results.

The advection of very dry air from the desert land mass surrounding the Gulf over the cooler waters results in the unusual situation of weak convection being driven entirely by a huge latent heat flux (up to 250 Watts per square meter) against a downwards sensible heat flux. The vertical gradients in the sensible and latent heat flux are such that the convective layer reaches a maximum depth of approximately half the boundary layer depth, the upper part of the layer being stable. A study of local similarity scaling shows that the scaling could be applied successfully across the full depth of the boundary layer, in spite of the change in stability. The extreme conditions highlight the occasional inconsistencies published in the literature in the definition of the temperature scale in various similarity schemes. This work was presented at the 13th Symposium on Boundary Layers and Turbulence in January 1999, and has been accepted for publication in Boundary-Layer Meteorology.

Coastal Waves 1996

Data on the structure of the marine atmospheric boundary layer over the coastal ocean was collected during 1996. The research has focused on the topographic constraints on the marine atmosphere and interactions with the coastal ocean.

The sea surface temperature (SST) pattern is determined by the wind stress and wind stress curl. The wind stress drives mixing, but the curl becomes a significant factor in the spatial variability away from the direct influence of the coastal barrier. Nearshore there is nearly uniform cold water associated with upwelling adjacent to a fixed barrier. Here variations in the stress do not appear to be important. Providing there is a constant wind stress, upwelling occurs. Further offshore, the pattern in the sea surface temperature shows regions of warm water and regions of cold water in patches about 20 km in diameter. Here there is little correspondence between the SST pattern and the wind stress. However, the wind stress curl shows a remarkably similar pattern. Regions of positive curl correspond with cold water and regions of negative curl correspond with warm water. Positive curl implies divergence in the ocean mixed layer and a shallowing of the pycnocline. Negative curl implies convergence in the ocean mixed layer and a deepening of the pycnocline. If the mixed layer is shallow, the wind stress will drive entrainment of colder water into the mixed layer at a faster rate than in a deeper mixed layer. The wind stress curl can account for this pattern. It should be noted that the sea surface temperature pattern and wind stress curl were measured completely independently.

The buoyancy flux corresponds well with the SST pattern. Negatively buoyant regions correspond with the coldest water and large positively buoyant regions correspond with the warmest water. This stable stratification supports interactions between gravity waves and turbulence. Atmospheric waves are frequently observed. Originating at the marine layer inversion, these waves may propagate throughout the boundary layer modulating the surface layer fluxes.

The wind stress pattern does not follow the wind field directly. Observed low values of stress coincide with regions where the bulk flux parameterizations predicts high wind stress values. Some of the scatter in the eddy correlation fluxes can be explained by the relative height of the measurements compared with the depth of the boundary layer. By scaling the measured fluxes with the depth of the boundary layer, we find that the 30 m level measurements underestimate the surface stress by about 0.3 Pa. However, this does not explain most of the observations. We conclude that gravity waves originating at the boundary layer inversion and presence of a wind speed jet maximum at the inversion modify the surface fluxes. Lidar measurements add some support for this notion. Aerosol backscatter lidar data can be used to determine the coherence of the vertical structure of the boundary layer. By computing a “coherogram”, we can determine the frequencies where there is significant vertical “coupling”, which implies a cause and effect relationship between processes at different levels in the boundary layer. Coincident in situ stress measurements are even more revealing, showing a reduction in the wind stress in regions of high vertical coherence. It is possible that the wind stress at the sea surface is less than would be predicted by a simple relationship with the wind speed, due to the presence of waves and the wind speed jet, which suppresses turbulence in this case.

The consequence of this for the sensible and latent heat fluxes is generally a suppression of the flux at wave scales and hence the bulk estimate of the scalar fluxes tends to overestimate them for a given wind speed in stable conditions. We observe good correspondence between the eddy correlation and bulk fluxes in unstable conditions.

Analysis of the NCAR C-130 data shows that the thinning and acceleration of the marine atmospheric boundary layer corresponds to a supercritical expansion fan. Local clearing in the marine stratocumulus occurs within the expansion fan, where the layer thins beneath the lifting condensation level. Layer-averaged maps of the layer height, speed, and Froude number show that the flow is transcritical, ie subcritical upstream flow became supercritical as it passes around Cape Mendocino. These features are reproduced with a transcritical shallow-water model which simplifies the coastline into an infinitely high coastal wall with several bends. The model indicates a hydraulic jump at a downstream bend, which correspondes to an increase in the layer depth viewed by the aircraft's lidar. The model shows that when the Cape Mendocino topography protrudes into the upstream flow, it exerts an upstream influence on the oncoming flow, namely a thickening and slowing within a Rossby radius of the coast. For all simulations, the along- and across-shore extent of the supercritical region downstream of the cape exceeds the Rossby radius.

This work implies that the thinning and accelerating of flow around coastal promontories observed during Coastal Waves 96 may be explained as that of a shallow layer of fluid which, when supercritical, supports expansion fans. During summer months, the marine atmospheric boundary layer is topped by an inversion and is characterized by strong along-coast winds. Under these conditions, the flow at capes is likely to be similar to those investigated here.

IMPACTS

The CW96 results reported thus far indicate that the parameterization of surface fluxes in stable conditions needs further consideration. Most measurements, to date, have been obtained over land and the transfer coefficients have not been verified over the ocean. The spatial and temporal relationship between the upper ocean and lower atmosphere should guide model coupled development applicable to coastal environments. The results recommend very high spatial resolution to resolve the features on scales of 20 km. The present 9km high resolution models may have too course grids. The results apparantly indicate rapid ocean response to wind forcing; however, this does not rule out significant advection within the ocean. More detailed, coincident measurements of the upper ocean and atmosphere are required to resolve this effect.

The SHAREM 115 results provide insight into the variability of the boundary layer and effect on radar propagation. This has the potential to impact how environmental data is used in radar propagation codes and suggests that greater awareness of the spatial variability of the boundary layer is essential to reduce the uncertainty in predicting ducting conditions.

TRANSITIONS

The CW96 project has provided NRL Monterey with an aircraft data set for COAMPS evaluation of coastal marine layer in presence of strong low-level wind speed jets. Real-time test and evaluation of the model was completed during the field phase of the study. Information on the spatial structure of the surface layer has been provided to help refine the model scales requires to develop a fully interactive ocean-atmosphere model. This work is conducted in collaboration with Drs. Stephen Burk and William Thompson at NRL Monterey.

The results from SHAREM 115 have been used to develop a test and evaluation strategy for the rapid environmental assessment (REA) concept applied to EM/EO propagation. This work was completed in collaboration with Dr. Andreas Goroch at NRL Monterey. Information has been transitioned to Mr.

David Lewis, Maritime Warfare Centre, Portsdown, CMDR Mark Windsor, CINCFLEET, Mr. Jon Turton, Meteorological Support Group, Ministry of Defence, and Mr. Patrick Jackson, Surface Warfare Development Group, USN, and other interested parties. The observed propagation conditions from SHAREM 115 are being used by Professor B. W. Atkinson of the University of London to provide a comparison with a mesoscale modelling study of radar propagation conditions over the Persian Gulf, commissioned by the UK Ministry of Defence.

RELATED PROJECTS

This project is related to an ASSERT award (N00014-97-1-0762), which is supporting three graduate students. One investigating the dynamics of the coastal flow, another is studying the radiative properties of boundary layer clouds, and the third is working on a preliminary investigation of fog.

PUBLICATIONS

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